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Land Carbon Cycle Dynamics and Applications of Seasonal Forecasts

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BK21 Seminar Series: New Frontiers of InfraSPHERE

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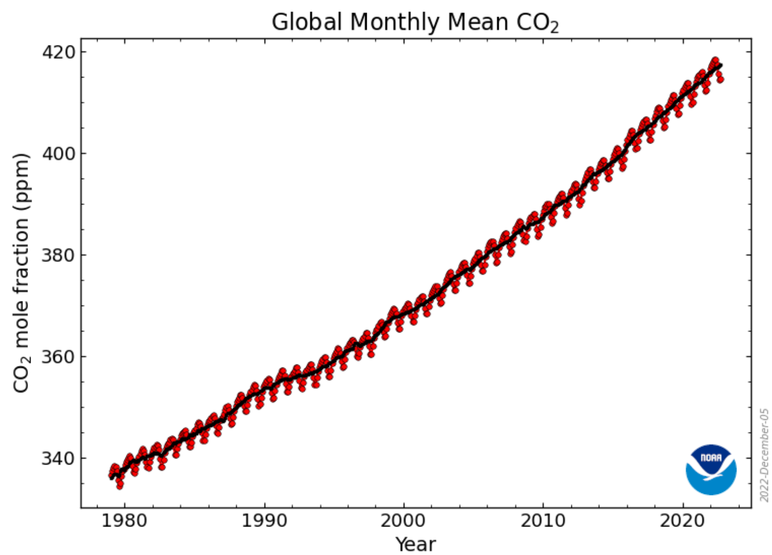
Overview of research themes

1. Land carbon dynamics and forecast skill
2. Land-Atmosphere coupling
3. Carbon-water interactions
4. Application of seasonal forecasts to resources management and support for decision-making processes

Carbon in the atmosphere

Global mean "*Carbon dioxide* (CO_2)"



https://gml.noaa.gov/ccgg/trends/

The growth rate of the atmospheric CO_2 concentration has gradually increased.

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"Extra carbon" in the atmosphere

- At the pre-industrial period, the Earth's carbon cycle was in equilibrium with 280 ppm of CO_2 in the atmosphere.
- Anthropogenic carbon emission has been put into the atmosphere since around 1850.
- Warming is attributed to the remaining "***extra carbon***" in the atmosphere.

418.4 ppm
(as of Mar 1, 2023)

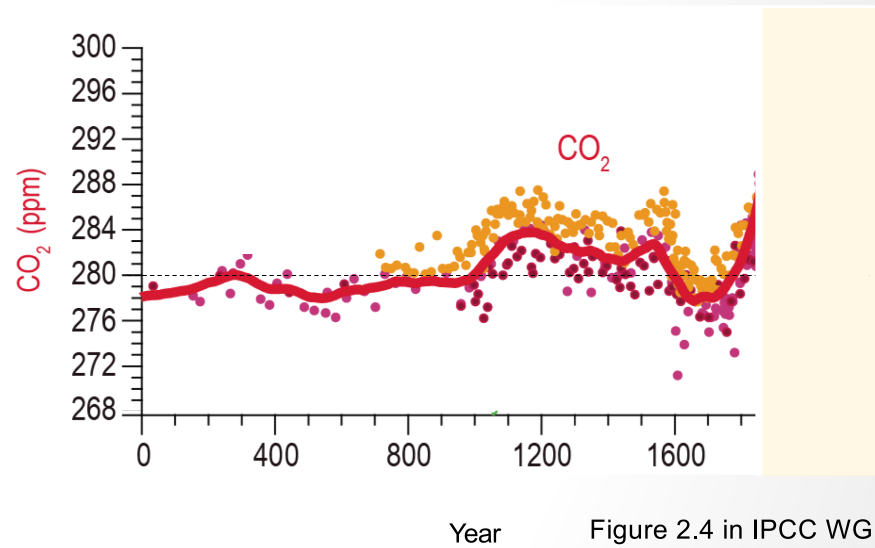


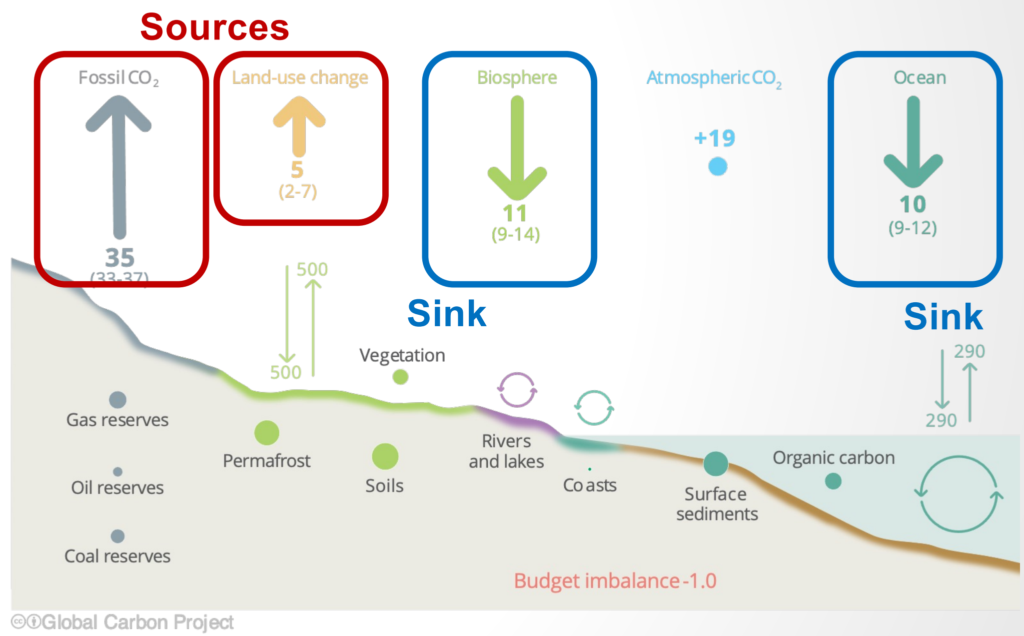
Figure 2.4 in IPCC WG1 Ch2

(Q) Does the atmosphere retain all amount of the extra carbon emitted by anthropogenic activities?

Dynamically changing global carbon cycle

- Carbon sources
  - Fossil emissions in the NH.
  - Land-use emissions in the tropics.
- No sink of CO_2 in the atmosphere
  - Only about a half of CO_2 emissions remain in the atmosphere, causing warming and climate change.
- Carbon sinks
  - Ocean sinks
  - Land sinks
- The emitted carbon moved the global carbon cycle away from an equilibrium and into a dynamic, transient state.

$$\boxed{\frac{dCO_2}{dt}} = \boxed{\text{Emission (carbon sources)}} - \boxed{\text{Removal (carbon sinks)}} + \cancelto{0}{\text{production}} - \cancelto{0}{\text{loss}}$$



Global Carbon Project 2022

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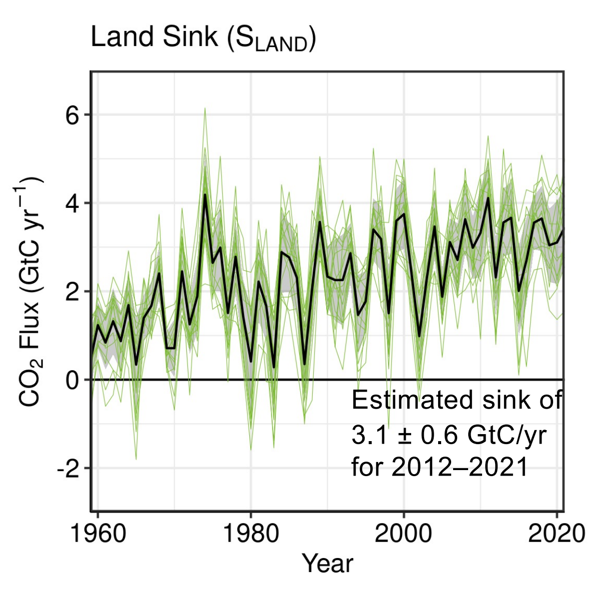
Terrestrial carbon cycle

- The size of carbon sink controls the amount of carbon in the atmosphere.
- Land biosphere currently absorbes ~¼ of emitted CO_2.
- High variability of the land carbon sink
  - Year-to-year variation influenced by environmental conditions.
- IPCC AR6: “the ocean and land carbon sinks are projected to be less effective”.
  - If land’s capability to absorb carbon decreases, climate change and warming may be accelerated.



It is important to understand the processes of the **land carbon dynamics,** intertwined with water and energy cycles on land and coupled to the atmosphere.

Friedlingstein et al 2022; Global Carbon Project 2022; IPCC AR6 WG1 Glossary

Research themes

[Theme 1] Land Carbon Dynamics and Predictability

- Seasonal forecast skill of land's carbon uptake

[Theme 2] Land-Atmosphere Coupling

- Impacts of a regional spring drought on land and atmospheric carbon

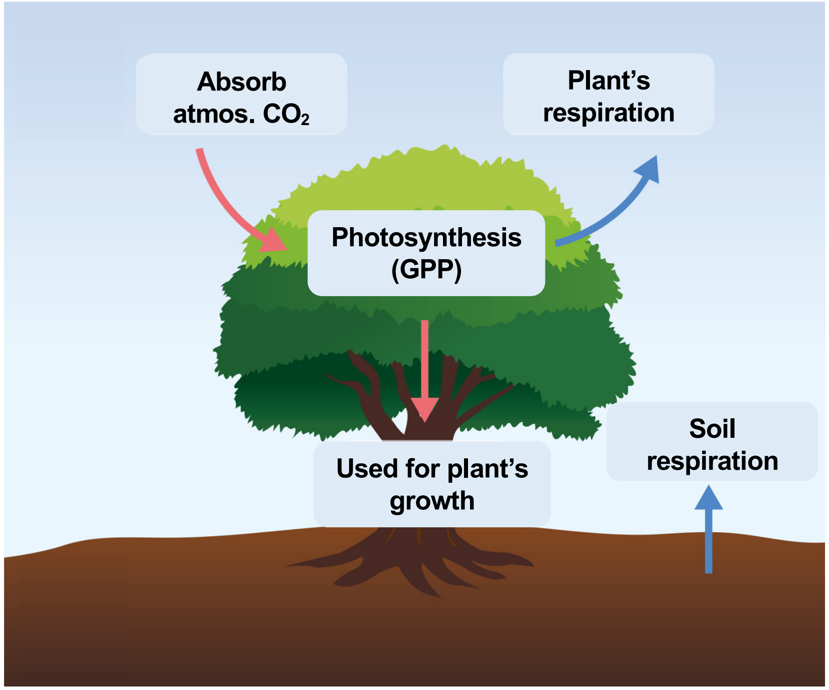
[Theme 3] Carbon-Water Interactions

- Improvement of streamflow modeling and hydrometeorological predictability by inclusion of carbon dynamics

[Theme 4] Application of seasonal forecast and climate projection to natural resources management and support for decision-making processes

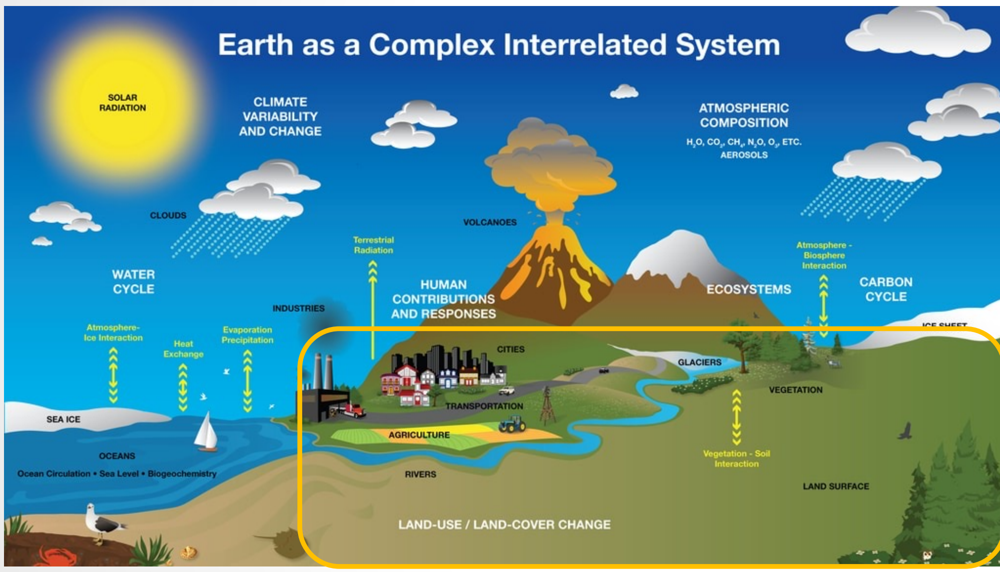
- Effects of climate change and land-use on tropical hydrology and hydropower
- Sub-seasonal water forecasts to support decision-making processes

Carbon dynamics on land

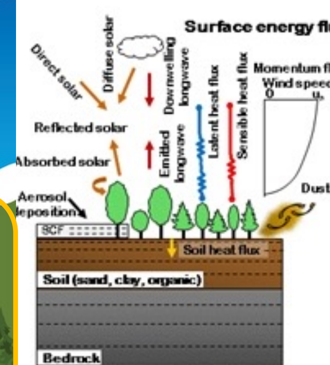


Net carbon uptake by land ecosystem
= Gross Primary Production – Respirations – Fire – Land use

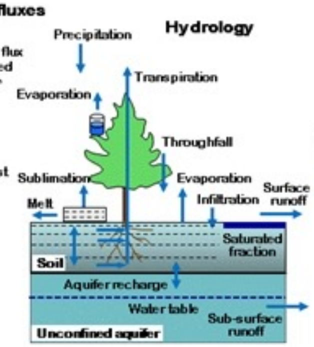
Modeling the terrestrial ecosystem



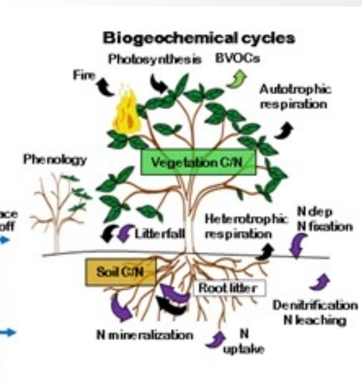
Energy cycle



Water cycle

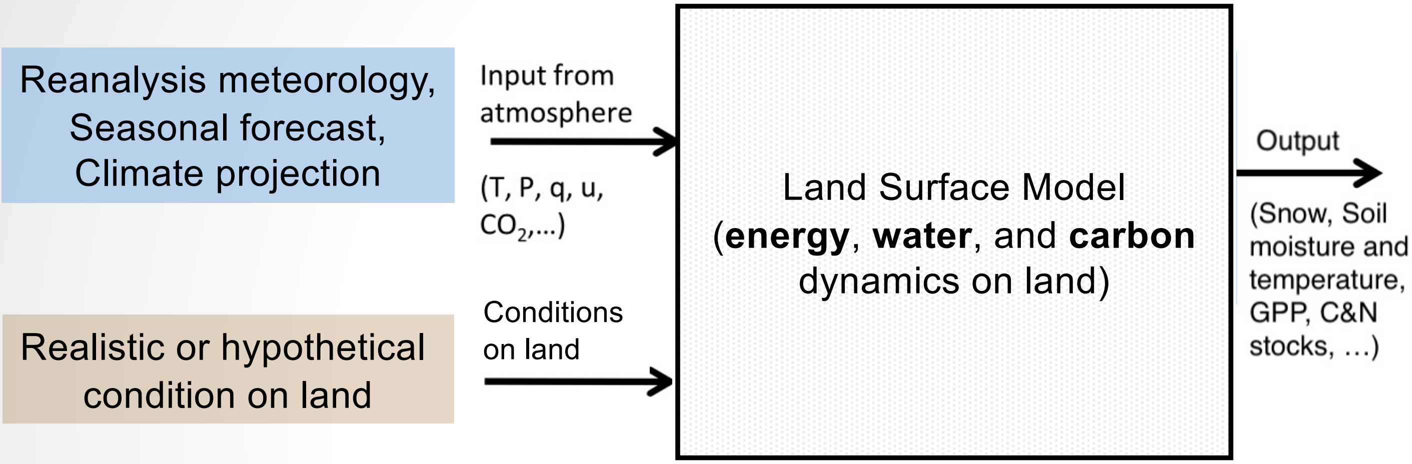


Carbon cycle



https://www.cesm.ucar.edu/models/clm

Land Surface Model (LSM)



- Inputs
  - Meteorology (e.g., air temperature, rainfall, radiation)
  - Initial conditions on land (e.g., status of vegetation, snow, and soil)
- Outputs
  - Water variables (e.g., soil moisture, runoff) and carbon variables (e.g., GPP)
- Use offline (if meteorology is prescribed) or coupled to the atmosphere in an ESM.

NASA's Catchment-CN land model

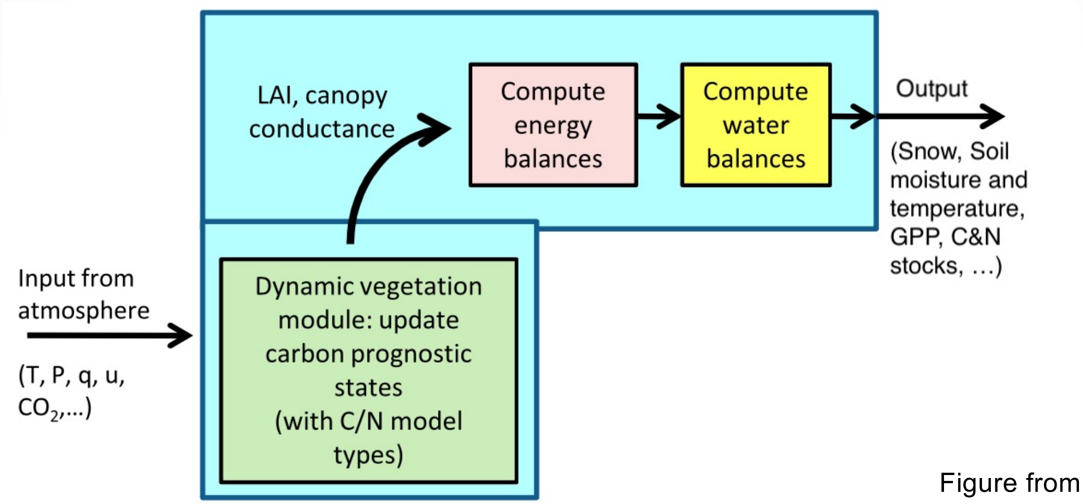


Figure from Koster et al. (2014)

- Use energy and water dynamics from Catchment model (Koster et al., 2000).
  - Dynamically treats the spatial variation within each hydrological catchment.
- Merged carbon and nitrogen dynamics from Community Land Model (v4, now v5.1).
- Energy and water dynamics at every 7.5 mins and carbon dynamics at every 90 mins.

How Catchment-CN computes land carbon dynamics

Leaf photosynthesis

- Farquhar model (Farquhar et al. 1980, Collatz et al. 1991 and Collatz et al.1992)*
- The minimum value of Rubisco-limited photosynthesis (ω_c), light-limited photosynthesis (ω_j) and export-limited photosynthesis (ω_e).

$$A = \min\left(\omega_c, \omega_j, \omega_e\right),$$

$$\omega_c = \begin{cases} \dfrac{V_{\mathrm{cmax}}(c_{\mathrm{i}} - \Gamma_*)}{c_{\mathrm{i}} + K_{\mathrm{c}}(1 + \frac{o_{\mathrm{i}}}{K_{\mathrm{o}}})} & \text{for } C_3 \text{ plants} \\ V_{\mathrm{cmax}} & \text{for } C_4 \text{ plants} \end{cases}$$

$$\omega_j = \begin{cases} \dfrac{(c_i - \Gamma_*)4.6\phi\alpha}{C_i + 2\Gamma_*} & \text{for } C_3 \text{ plants} \\ 4.6\phi\alpha & \text{for } C_4 \text{ plants} \end{cases}$$

$$\omega_e = \begin{cases} 0.5V_{\mathrm{cmax}} & \text{for } C_3 \text{ plants} \\ 4000V_{\mathrm{cmax}}\dfrac{c_{\mathrm{i}}}{P_{\mathrm{atm}}} & \text{for } C_4 \text{ plants} \end{cases}$$

V_{cmax} = maximum rate of carboxylation
c_i = internal leaf CO_2 partial pressure
ϕ = absorbed photosynthetically active radiation

Respirations

- Autotrophic respiration (R_a) and heterotrophic (soil) respirations (R_h) are based on the Q_{10} function of temperature and moisture.

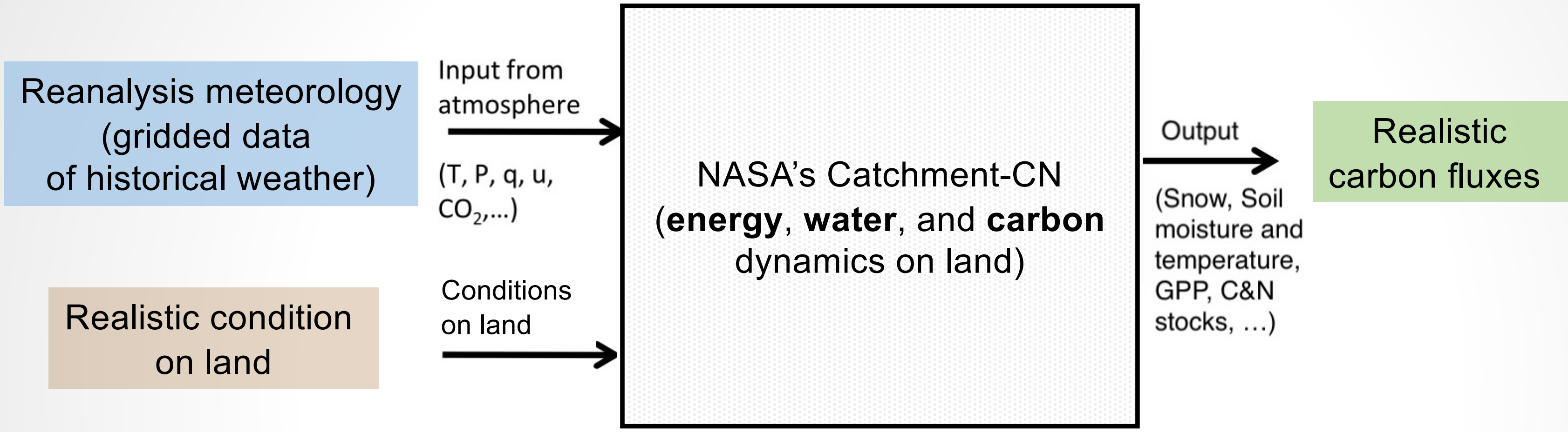
Net Biosphere Production (NBP)

- **NBP > 0** : **Land** is a carbon **sink**
  (**Atmosphere** is a carbon **source**)
- **NBP < 0** : **Land** is a carbon **source**
  (**Atmosphere** is a carbon **sink**)

$$NBP = GPP - R_a - R_h - F - LU$$

*also as in CLM4 (Oleson et al., 2010)

Land Surface Model for evaluating carbon fluxes



- Inputs
  - Reanalysis meteorological variables (e.g., air temperature, rainfall, radiation)
  - Realistic initial condition on land
- Outputs
  - Realistic water variables and carbon variables (e.g., GPP and net carbon exchange)

Evaluation of carbon fluxes from Catchment-CN

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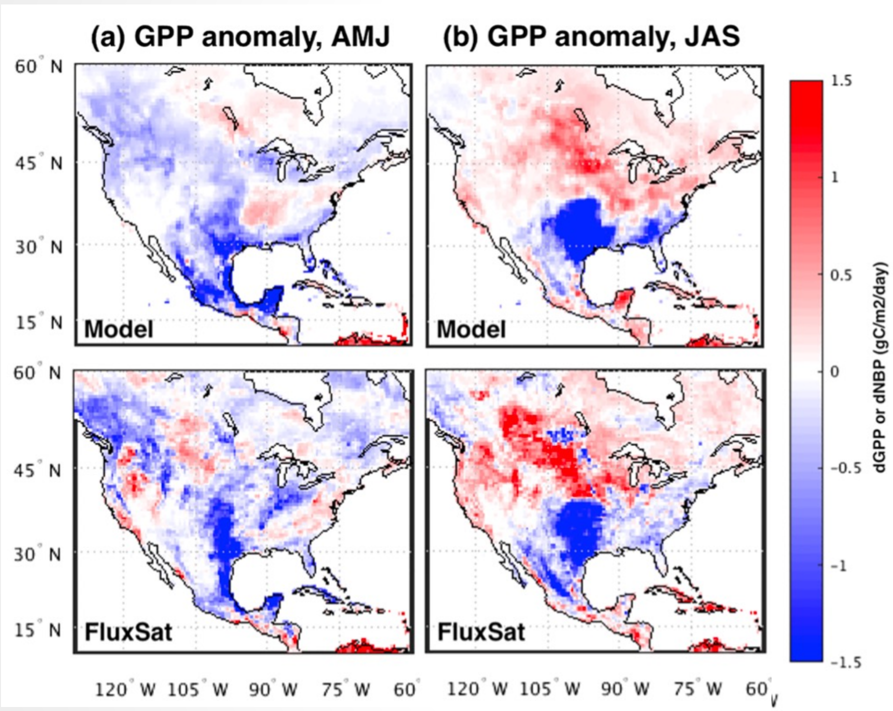
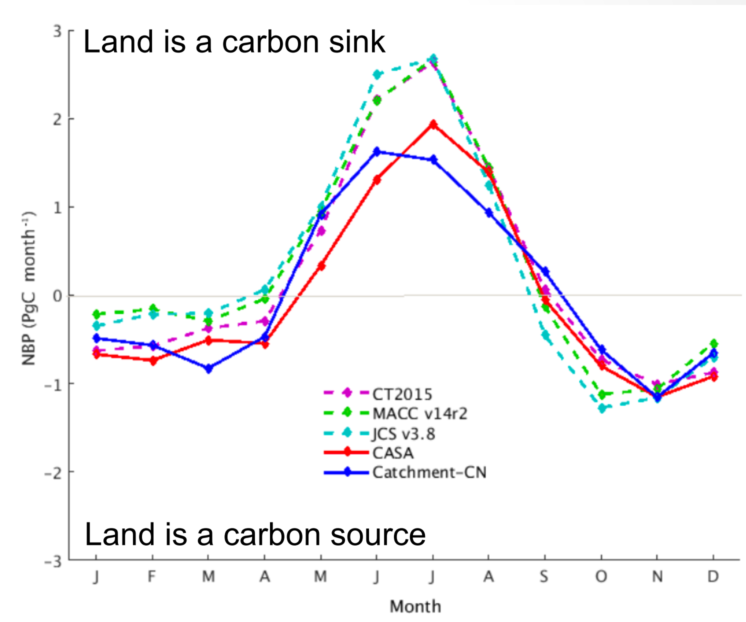
Total carbon uptake (GPP) by land



Lee et al. (2020), *JGR-bio*

Net carbon exchange

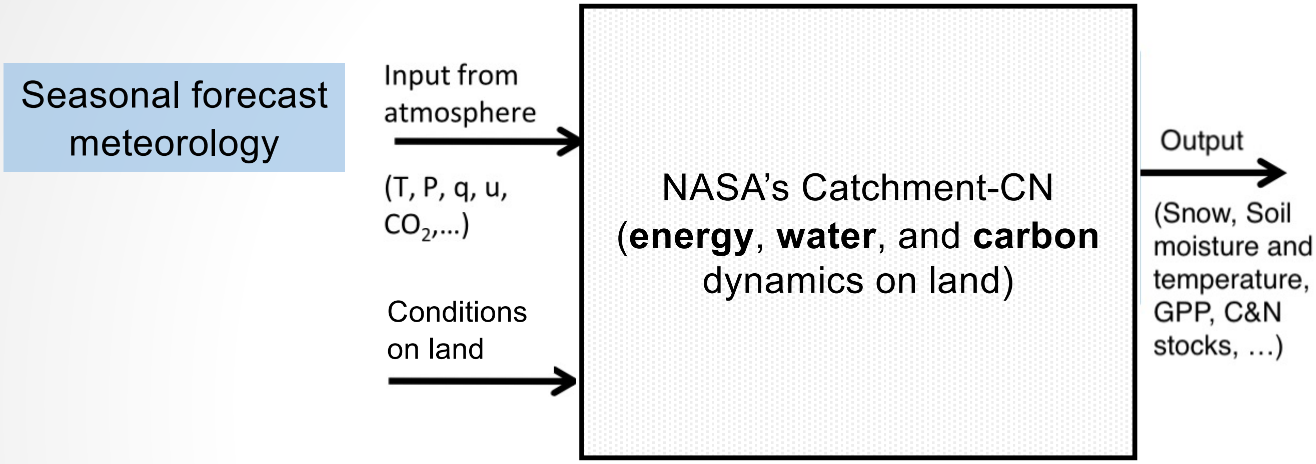


Lee et al. (2018), *Biogeosci.*

Carbon forecast

- New area of research
- *Carbon forecasting*, in general, has been addressed only in a few studies. (e.g., Rousseaux and Gregg, 2017; Park et al., 2019; Séférian et al., 2018; Lovenduski et al., 2019).
- To improve the forecast system of the Earth, we need the information about the system's behavior with inclusion of the carbon cycle.
- Seasonal carbon forecasts can eventually support a wider range of end-user applications such as wildfire management, forestry, and agriculture.

Land Surface Model for carbon forecast

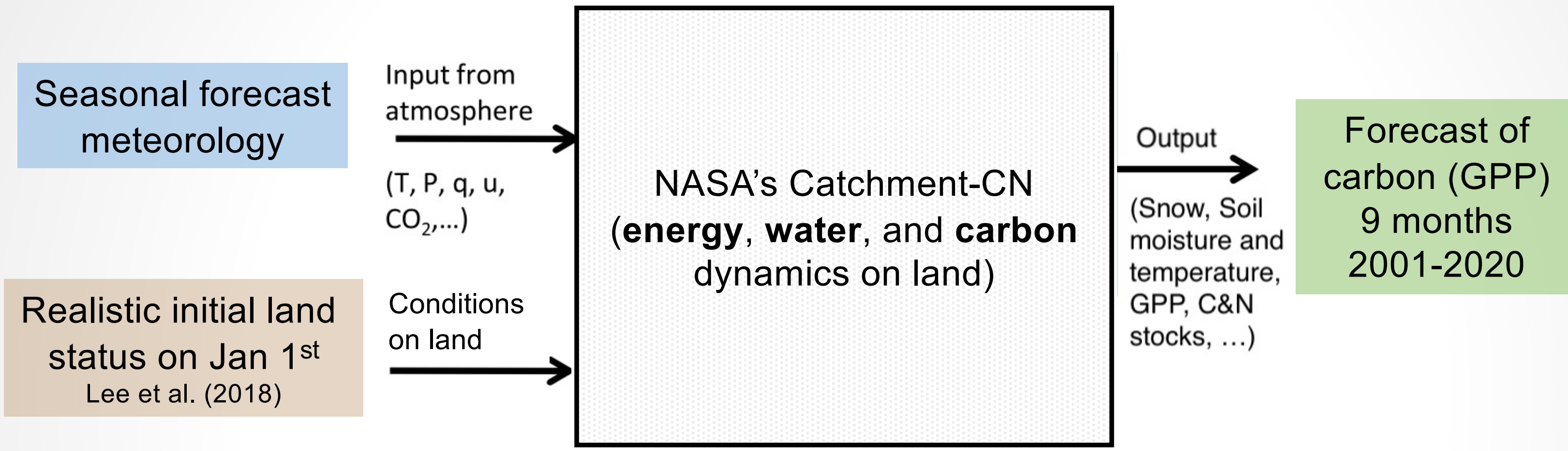


Seasonal forecasts of meteorology

- Longer than a week and up to several months
- NASA's GEOS subseasonal-to-seasonal (S2S) meteorological forecasts
  - Up to 9 months, initialized at every 5 days.
- Multiple projections (ensemble forecasts) due to atmospheric chaos

- The forecast skill stems from:
  - Ability to translate the initial states into future states through proper representation
  - Evolution of coupled climate modes

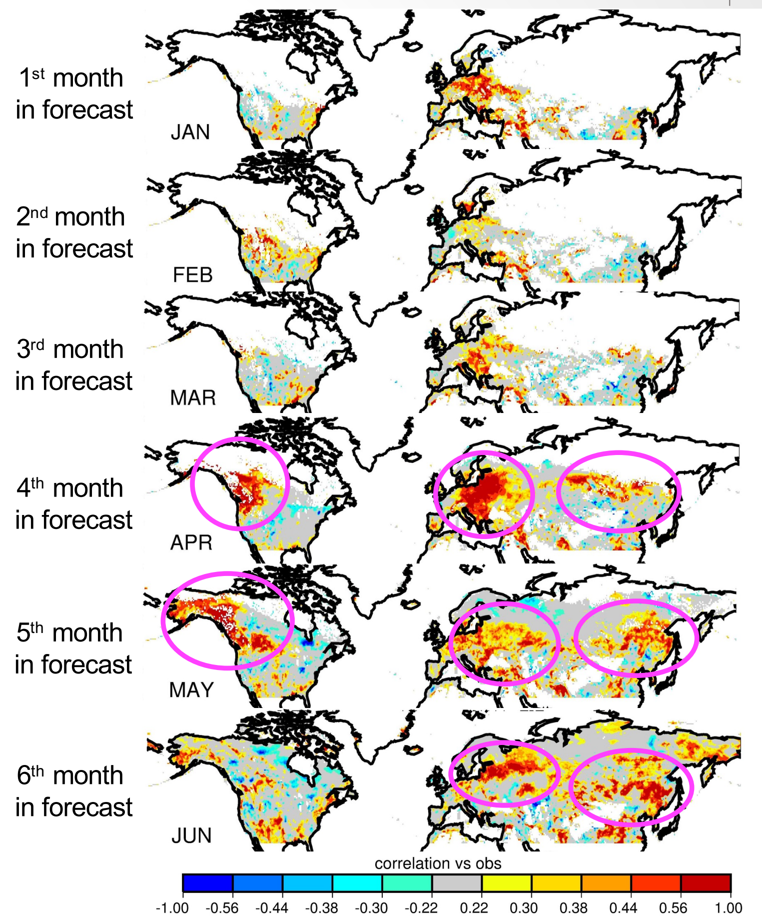
Land Surface Model (LSM) for forecasting carbon fluxes



- Forced with bias-corrected, retrospective seasonal forecast meteorology.
- Ensemble carbon forecasts (Jan 1st – Sep 30th) generated by Catchment-CN
- Evaluated with FluxSat GPP derived from MODIS reflectances (Joiner et al., 2018)
- Temporal correlation coefficients of 20 pairs (2001-2020) between forecast and obs.

Skillful forecast of land's carbon uptake

- Skillful GPP forecast in northwestern North America, eastern Europe, and Eurasia.
- High forecast skill in April, May, and June.
- Meteorological forecast skill does not explain the high carbon forecast skill after 3rd lead month.
- Other factors must contribute to the carbon forecast in mid- and high-latitudes during spring.



0.22, 0.30, 0.38, 0.44, and 0.56 being statistically different from zero at the 66.7%, 80%, 90%, 95% and 99% confidence levels, respectively.

Lee et al. (2022). *Geophys. Res. Lett.*

Snowcover removal timing and a supplemental experiment

- Snow cover removal day was defined as:
  - When daily snow mass becomes lower than 1 kg/m^2 (or 1 mm of snow water equivalent (SWE)) and,
  - The snow mass remains below the threshold for the following 7 consecutive days

- EXP suite
  - Same as CTRL, except for retaining the inter-annual variation of the CN initialization on Jan 1st and fixing other conditions as those in year 2013.
  - No inter-annual variability in forecast meteorology and snow and soil moisture initialization is allowed.

Contributions from snow and carbon initializations

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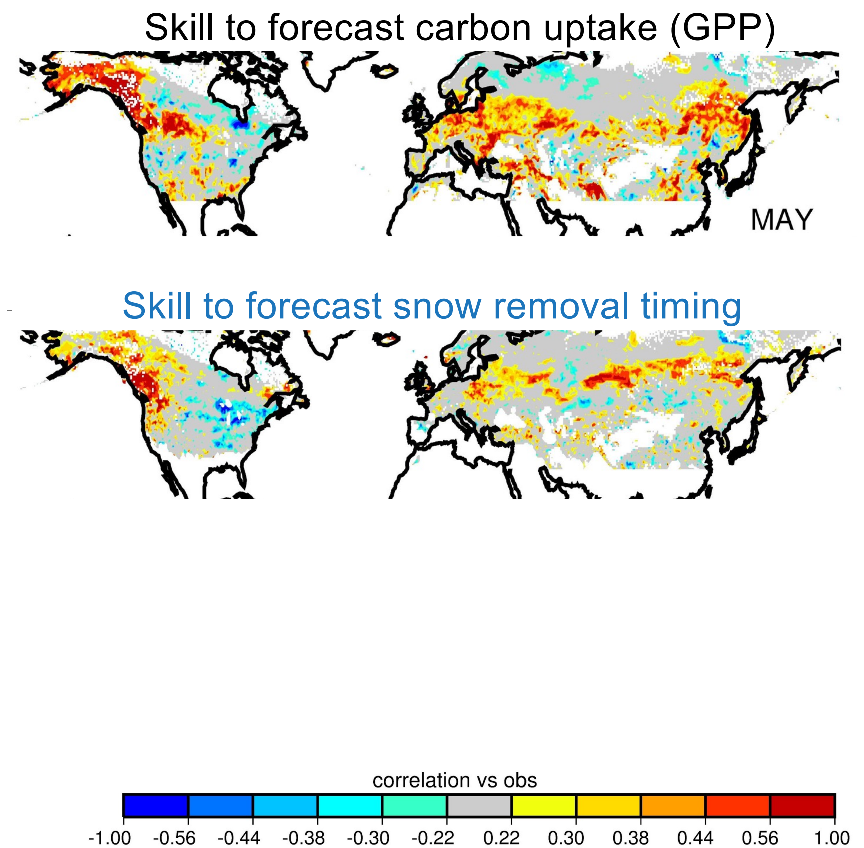
- Contribution of snow initialization
  - Northwestern N. America and Eurasia.
  - Snowpack initialized in January sits undisturbed until the snow melts away.
  - Help determine when the carbon uptake begins by vegetation.

- Contribution of carbon initialization
  - Southeastern Europe and eastern Asia.
  - Carbon storage represents relatively “slow” component of the Earth system.
  - Help set the stage for plant productivity.



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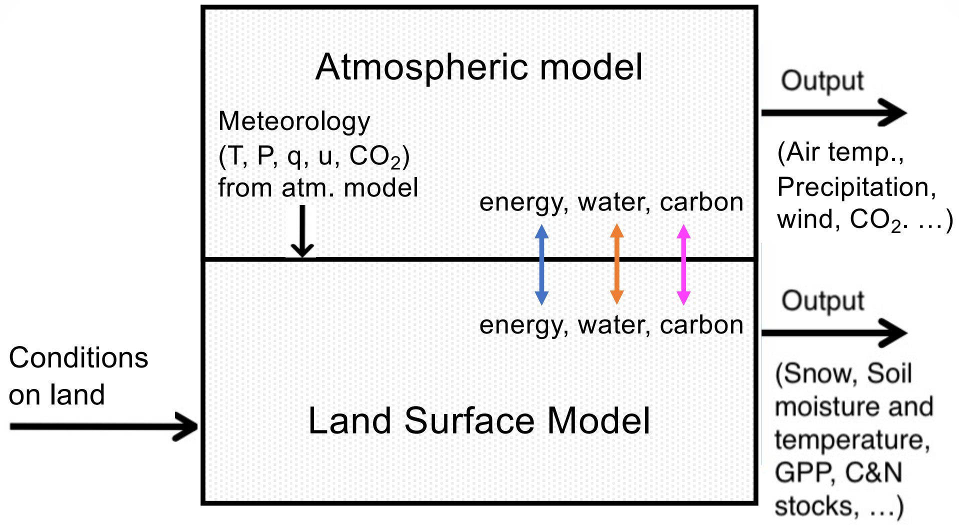
Land Surface Model coupled to the atmosphere

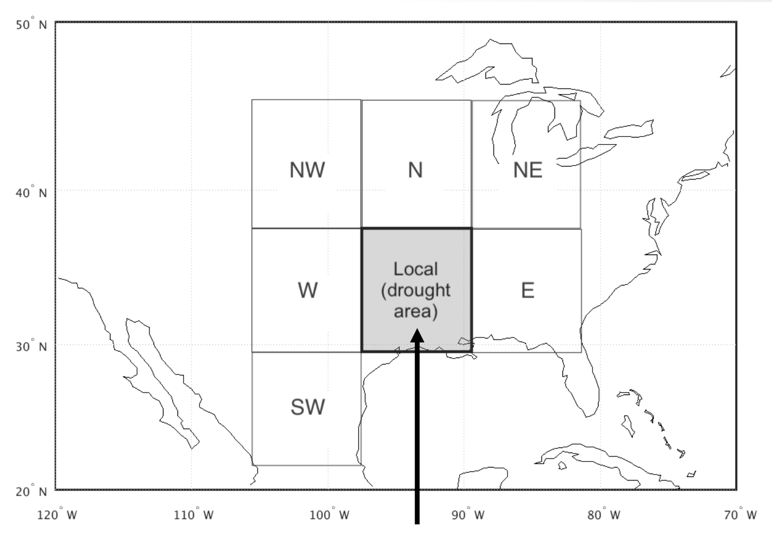


Coupled L-A configuration

- Allows coupled treatment of energy, water and carbon dynamics between the land and the atmosphere and feedback.
- Fully-interactive carbon cycle
  - Land provides net carbon exchange to and receives CO_2 from the atmosphere.

Impacts of a regional spring drought on carbon

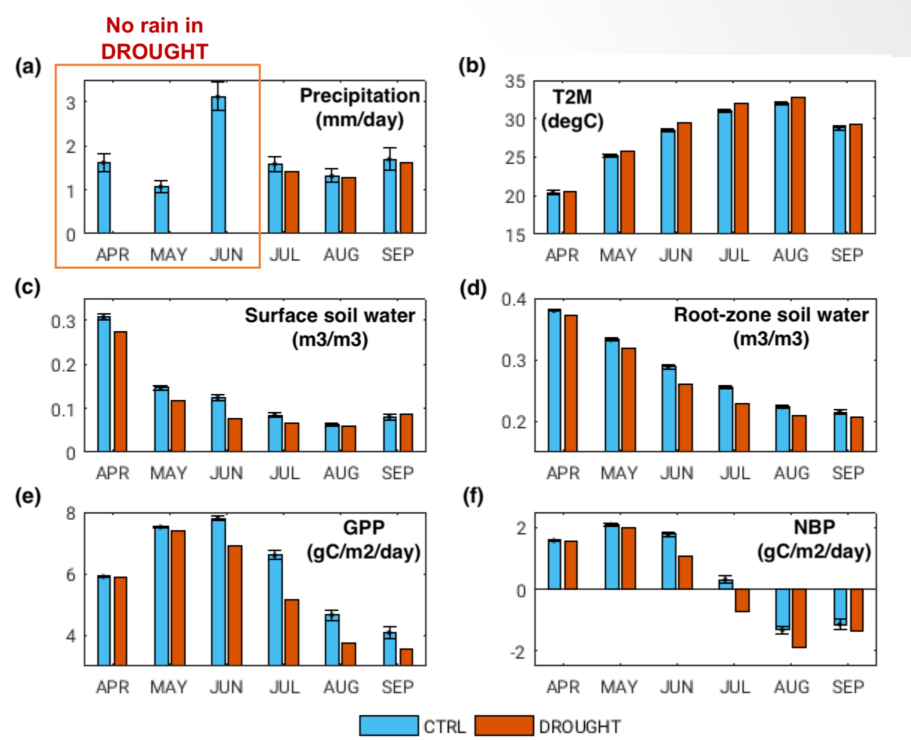
- Imposed an idealized spring drought (i.e., land receives no precipitation) over the lower Mississippi River Valley
- Drought for 3 months in April, May, and June.
- Followed by a 3-month recovery period in July, August, and September.
- Each suite (CTRL and DROUGHT) consists of 45 free-run, coupled simulations.



~500,000 km^2
(7° x 7°)

Changes in water and carbon on land by drought

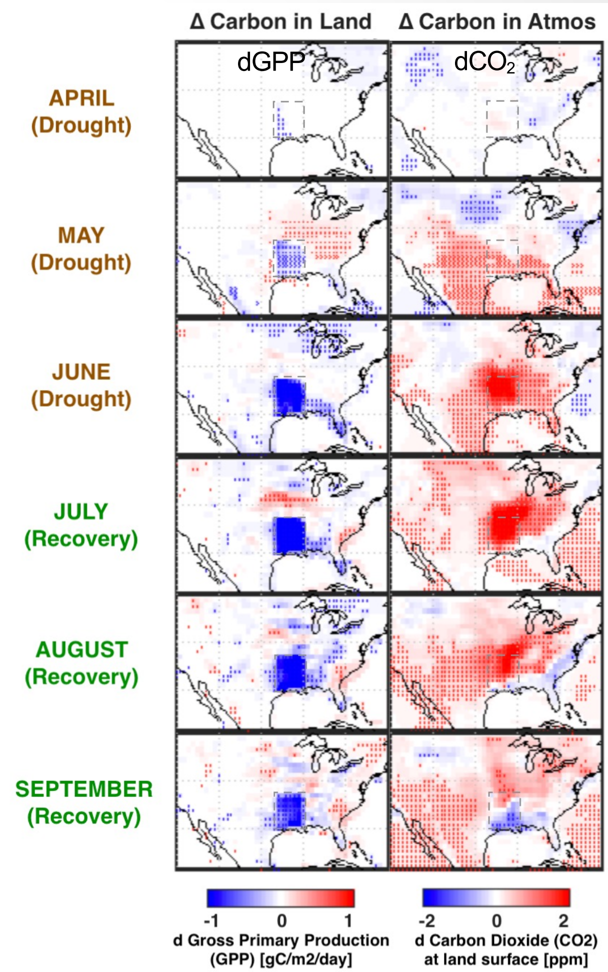
- A regional spring drought results in:
  - Increase in T_{air}
  - Depleted soil moisture
  - Decrease in total carbon uptake by land's vegetation (~23%)
  - Reduction in net carbon uptake
- Some effects remain even during the recovery period (July-September).



Lee et al. (2020), *JGR-bio*

Induced carbon anomaly via L-A coupling

- Impact is also shown in remote areas through induced-changes in meteorology.
- CO_2 anomaly extends over an area three times larger than the drought due to atmospheric transport.
- Surface CO_2 anomalies up to 3.57 ppm.
- Column-averaged CO_2 anomalies up to 0.78 ppm.
  - Values near the measurement uncertainty of current greenhouse gas observing satellites.



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[Theme 3] Carbon-Water Interactions
- S2S hydrometeorological prediction
- Water dynamics intertwined with the carbon cycle

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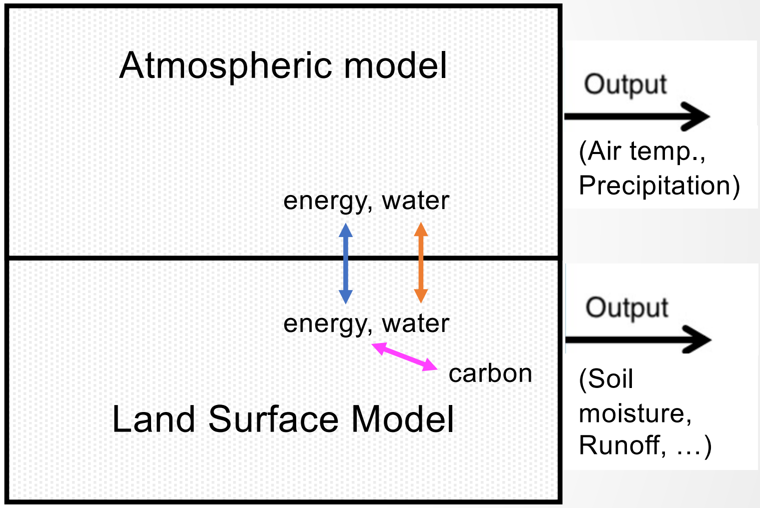
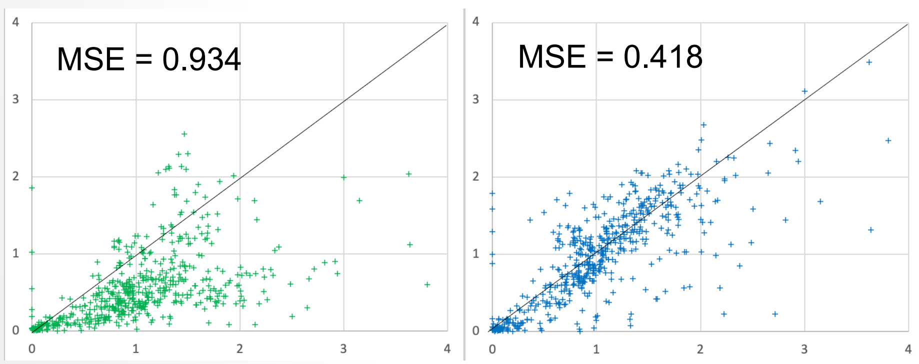
Improve sub-seasonal hydrometeorological prediction through enhanced treatment of carbon processes

- Ongoing funded project by NASA S2S Hydrometeorological Prediction
- PI: Randal D. Koster (NASA)
- Co-I: Eunjee Lee
- NASA's operational seasonal forecast system does not utilize carbon cycle dynamics in the full coupled model.
- To incorporate variations in canopy transpiration conductance and albedo (associated with the carbon cycle) to improve the sub-seasonal prediction.



Water dynamics intertwined with carbon processes

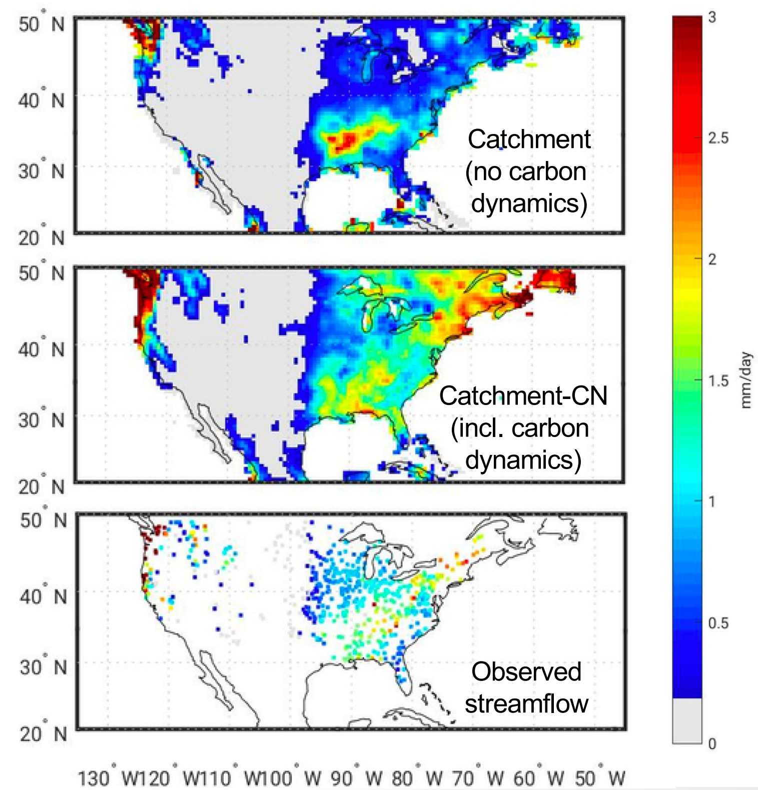
- Model streamflow in consideration of carbon dynamics agrees better with observed streamflow at gauges.



Model total runoff
(no carbon dynamics)

Model total runoff
(incl. carbon dynamics)

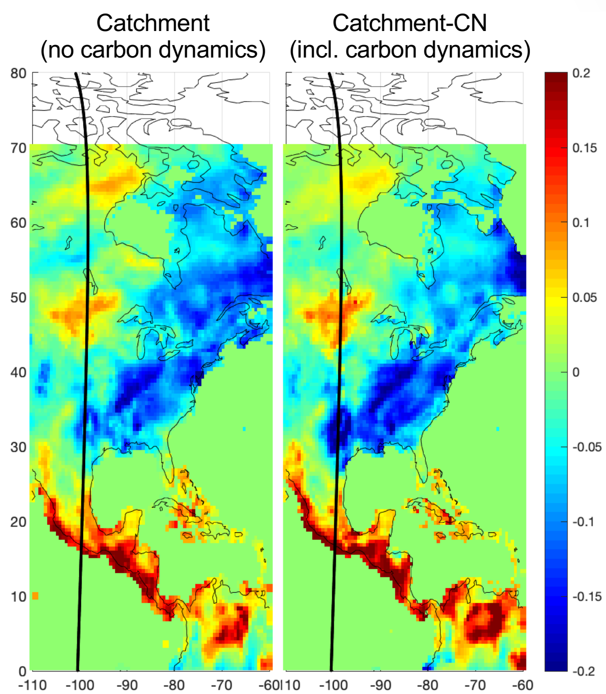
Mean streamflow (2001-2020)



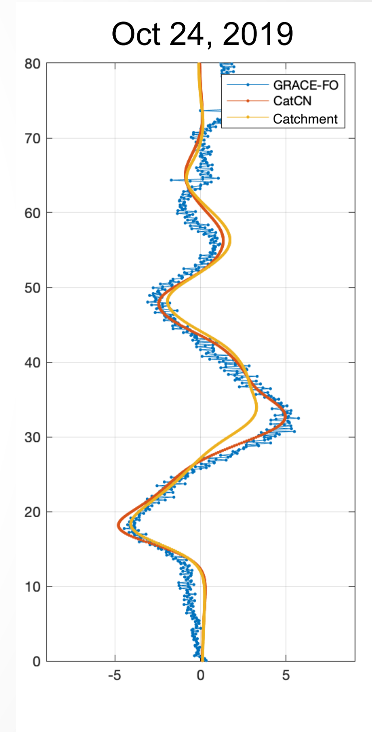
Water dynamics intertwined with carbon processes

- Anomaly of total water storage for a flash drought also agrees better with GRACE.

Anomaly in soil water



TWS anomaly during 2019 US flash drought



Plot from Shin-Chan Han

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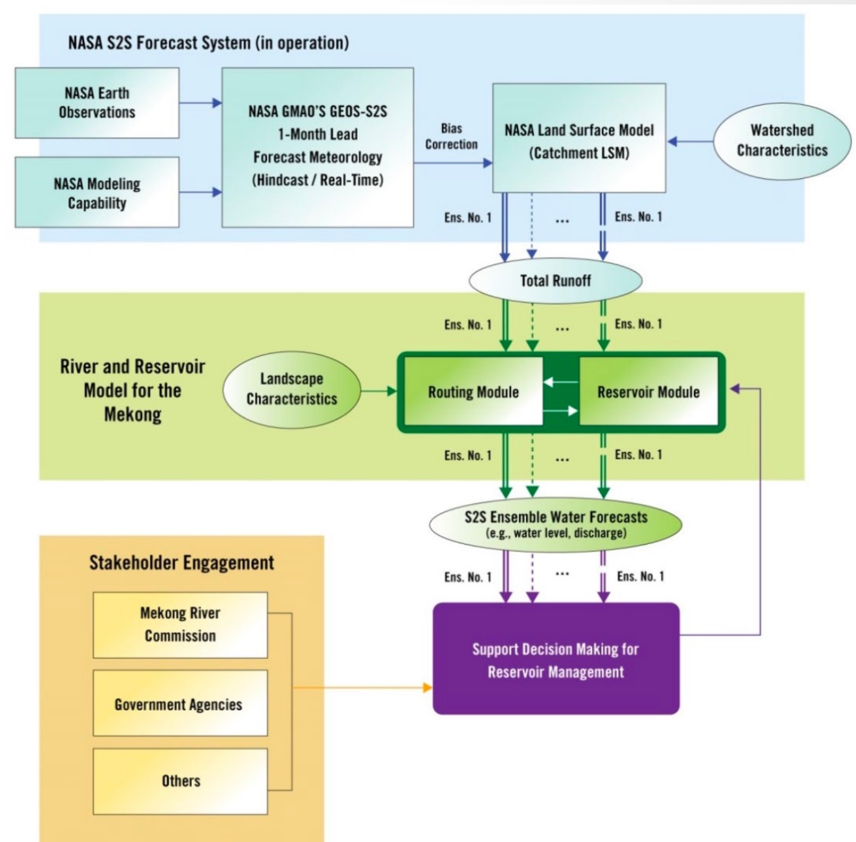
Developing sub-seasonal water availability forecasts for informed decision-making

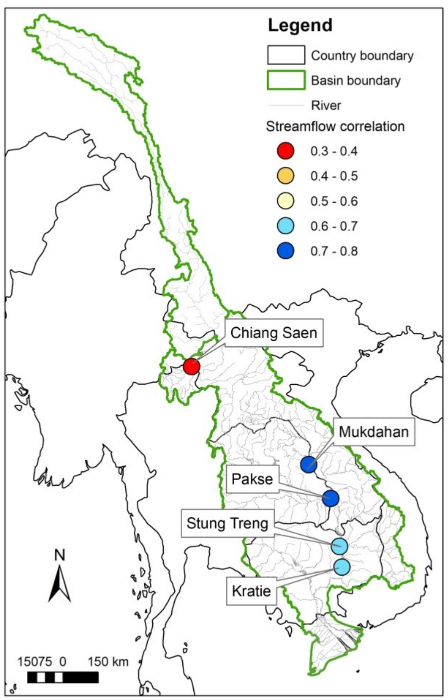
- Ongoing funded project by NASA SERVIR Applied Science Team
- PI: Mauricio E. Arias (USF)
- Co-Is: Eunjee Lee, Randy Koster (NASA), Miguel Laverde (ADPC)
- To improve the Mekong's water forecasts
  - Use NASA's seasonal forecast to increase temporal coverage to 30 days
  - Account for reservoir operations
- To provide real-time water forecasts to support decision-making in water resources management.



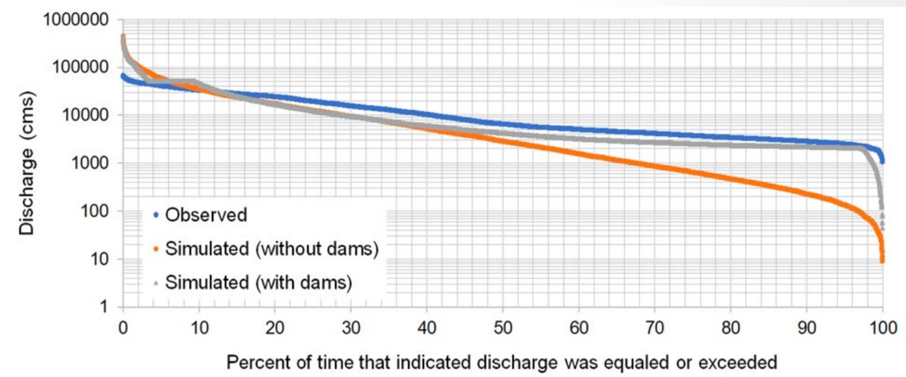
SERVIR preliminary results

- Reasonable skill to predict streamflow at the 1st forecast month.

Forecast skill
of streamflows
at 1st lead month



- Improved accuracy to reproduce observed discharge by incorporating the operations of large reservoirs.



Thank you for your attention!